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PROTON REACTION CROSS SECTIONS MEASURED IN THE BNL/AGS E943 EXPERIMENT

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ABSTRACT

We have measured proton reaction cross sections over a wide mass and energy range at the Brookhaven AGS accelerator. The samples were elemental Be, C, Al, Cu, W, and Pb; the measurements were carried out at ten incident proton kinetic energies in the range 0.54 to 7.8 GeV. The experiment was similar to an earlier experiment in the 200 – 550 MeV range by Renberg *et al.*[1] The new results are in good agreement with those of Renberg *et al.* at the overlap point near 550 MeV. The combined results of the two experiments show an energy dependence expected from the behavior of the nucleon-nucleon cross sections. The results are reproduced by calculations based on variants of the impulse approximation and Glauber theory.

I. INTRODUCTION

Codes such as MCNPX rely for their accuracy on well-measured (or calculated) cross section data. Among the most important cross sections are neutron total and proton reaction cross sections. These data are used directly in the codes, where they provide a sum on all reaction processes, and also indirectly through their use in the development of models (such as the optical model) that are used for the calculation of other reactions.

Very accurate (1%) measurements of neutron total cross sections in the 5 – 560 MeV range were recently carried out at LANSCE/WNR under the auspices of the Accelerator Production of Tritium (APT) project[2]. Since neutron measurements of such accuracy are very difficult above this energy range, we have undertaken proton reaction cross section measurements in the energy range 0.54 – 7.8 GeV. Proton reaction cross sections represent the sum of all possible reaction processes on a nucleus with the exception of elastic scattering. The measurements were carried out in the B1 beam line at the Brookhaven AGS accelerator as experiment E943. Measurements were made on elemental samples of Be, C, Al, Cu, W, and Pb. The accuracy achieved was approximately 3%. The results were used to test theoretical models for microscopic optical potentials based on the impulse approximation, a modified impulse approximation that accounts for nuclear-medium modification of the nucleon-nucleon interaction, and Glauber theory. The good agreement obtained with these models suggests that they are useful for calculating reaction cross sections where measurements have not been made.

II. EXPERIMENTAL DETAILS

The measurements were carried out by a transmission technique, in which the beam of protons was incident on a sample, and the transmitted protons (as well as reaction products) were detected in a coaxial array of six circular plastic-scintillator counters mounted downstream of the sample. The diameters of these counters ranged from 10.6 to 45 cm. The count rates in the detectors with the sample in and out of the beam were compared to obtain the sample transmission. The experimental arrangement and the analysis of the data were very similar to those in Ref. 1.

Particle identification was necessary, since the proton beam in the AGS B1 beam line is a mixture of electrons, muons, pions, kaons, and protons at a momentum selected by analyzing magnets upstream of the experiment. This was accomplished by time of flight between two 3-cm diameter beam counters separated by approximately 10 m upstream of the sample. Above 4 GeV/c momentum, time of flight identification was insufficient, and for these momenta a Cerenkov counter was used to separate out the protons. The two beam counters were also used to trigger the data taking electronics. When a coincidence between these counters was obtained, the pulse height and flight time (relative to the downstream beam counter) were recorded for all counters in the experiment.

The six samples were mounted on a wheel that rotated to a new position every 40 seconds. Two of the positions on the 8-position wheel were empty, in order to make the sample-out measurements. A second wheel placed upstream of the samples contained two polyethylene energy degraders that were positioned in the beam during the sample-out measurements. This ensured that the energy of the beam striking the main counters was approximately the same during the sample-in and sample-out conditions. Thicknesses of the samples were chosen so that their transmission was approximately 90%.

The six counters in the main counter array subtended six different solid angles as seen from the samples. The counters were mounted on cart that could be moved along the beam axis. At each energy, the cart was placed at two different positions to allow data taking at a total of twelve solid angles. The detector positions were chosen so that approximately the same range of elastic-scattering momentum transfer was encompassed at each energy.

In analyzing the data, cuts were made on the time of flight between the two beam counters to select incident protons. Analysis of the Cerenkov data to achieve particle separation at the higher momenta is currently in progress. Cuts were also made on the pulse height in all counters to ensure that low-energy pulses corresponding to Cerenkov radiation in the light guides leading from the circular counters to the phototubes was eliminated.

As was done in Ref. 1, a partial cross section at each solid angle was calculated from the measured sample-in to sample-out count-rate ratio. A correction was made for elastic scattering events that missed each counter, since the experimental technique assumes that elastically scattered protons are detected and therefore do not contribute to the measured attenuation in the samples. These corrections were made using elastic angular distributions calculated by Glauber theory[3]. Only counters for which this correction was smaller than 10% were included in the further analysis. The final value of the cross section was obtained by extrapolating the partial cross sections to zero solid angle. This extrapolation is needed to account for the fact that debris from a nuclear reaction in the sample may be detected in the counters, since such events will not contribute to the apparent sample attenuation. Fig. 1 shows an example of the behavior of the partial cross sections as a function of solid angle for the case of 1380 MeV protons incident on the Al sample.

Fig. 2 shows preliminary results for proton reaction cross sections on Al at the energies for which time-of-flight particle identification was sufficient. For these preliminary results the zero-degree extrapolations were made by eye. Combined statistical and systematic errors are estimated at 3%. The results are seen to be in good agreement with the experiment of Ref. 1 at the point of overlap near 540 MeV.

The combination of the present results and those of Ref. 1 clearly shows a rise in the reaction cross section in the region 500 – 1000 MeV. This behavior of the proton-nucleus cross section mirrors the energy dependence of the elementary nucleon-nucleon cross sections, shown in Fig. 3 for the proton-proton total cross section.

III. CALCULATIONS

The data in the present experiment and in Ref. 1 were used to test formulations of the microscopic optical potential. In microscopic optical potentials, the nucleon-nucleus potential is obtained by convolution of the nuclear density with an effective nucleon-nucleon interaction. The potential is used in a relativistically-modified Schrodinger equation to yield observables such as the neutron total and proton reaction cross sections. In the present work proton densities were taken from elastic scattering results as tabulated in Ref. 4, together with a reasonable assumption for the neutron densities. Results of such calculations for neutron total cross sections and the proton reaction cross sections of Ref. 1 are in the course of publication[2].

The dotted curve in Fig. 2 shows an impulse-approximation calculation based on the Franey-Love[5] effective interaction, which has been tabulated between 50 and 1000 MeV. It is in reasonable agreement with the data in the 400 – 1000 MeV region, but disagrees at lower energies. This deficiency is well understood to be due to the need for modifications of the effective nucleon-nucleon interaction in the nuclear medium. An empirical effective interaction in the 135 – 650 MeV range involving density-dependent modifications of the Franey-Love interaction has been reported by Kelly and Wallace[6]. Calculations based on this interaction, shown by the solid curve in Fig. 2, agree well with the data. Glauber theory[3] calculations avoid explicit use of a wave equation by using an eikonal approximation, and employ a simple description of the nucleon-nucleon interaction based directly on cross sections such as those shown in Fig. 3. Results of Glauber calculations, shown by the dot-dash curve in Fig. 2, are seen to provide a good description of the data at high energies where effective interactions based on the impulse approximation are not available.

IV. SUMMARY AND CONCLUSIONS

We have measured proton reaction cross sections on a set of samples spanning the periodic table at energies ranging from 0.54 to 7.8 GeV. The experimental arrangement was similar to that of Renberg *et al.*[1], who measured reaction cross sections in the 200 – 550 MeV range. The excellent agreement between the two experiments at the matching energy near 540 MeV suggests that the two sets of measurements may be used to delineate the energy dependence of proton reaction cross sections in the 500 – 1000 MeV region where the underlying nucleon-nucleon cross sections are varying rapidly. The energy dependence is well reproduced by calculations based on a modified impulse approximation and by Glauber theory, as illustrated by preliminary results on an aluminum sample. This result, together with a similarly successful reproduction of neutron total cross sections[2], indicates that these models may be useful for quantitative prediction of proton and neutron cross sections where data are lacking.

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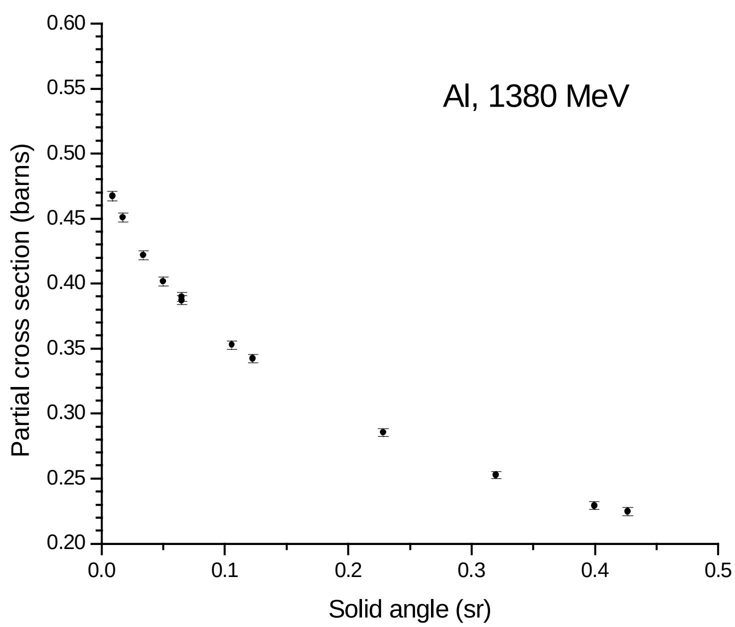

Figure 1. Example (for 1380-MeV protons on the Al sample) of the partial cross sections as a function of solid angle after the elastic-scattering correction. The final cross section is obtained by extrapolating to zero solid angle.

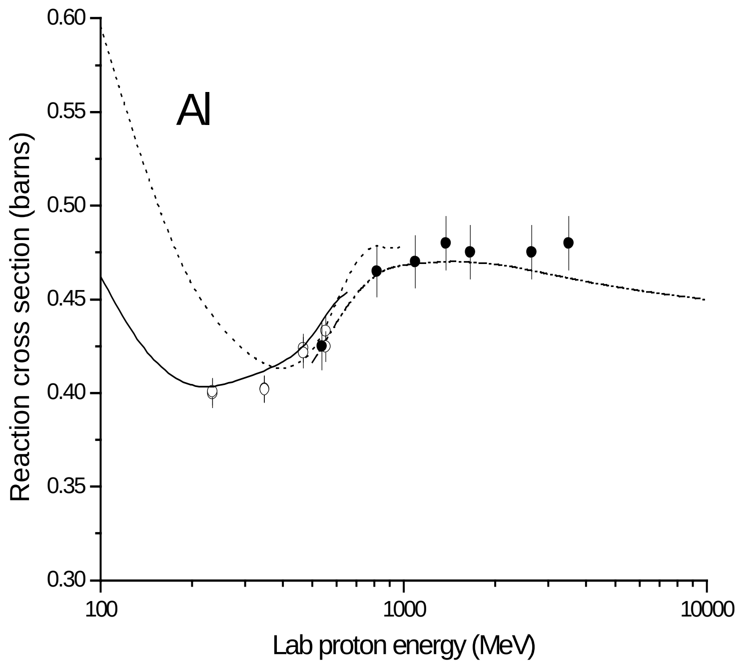

Figure 2. Preliminary results of the present measurements for aluminum are shown by closed circles; those of Ref. 1 by open circles. The calculated curves were made with the Glauber theory (dot-dash), impulse approximation (dotted), and a nuclear-medium modified impulse approximation (solid); see text.

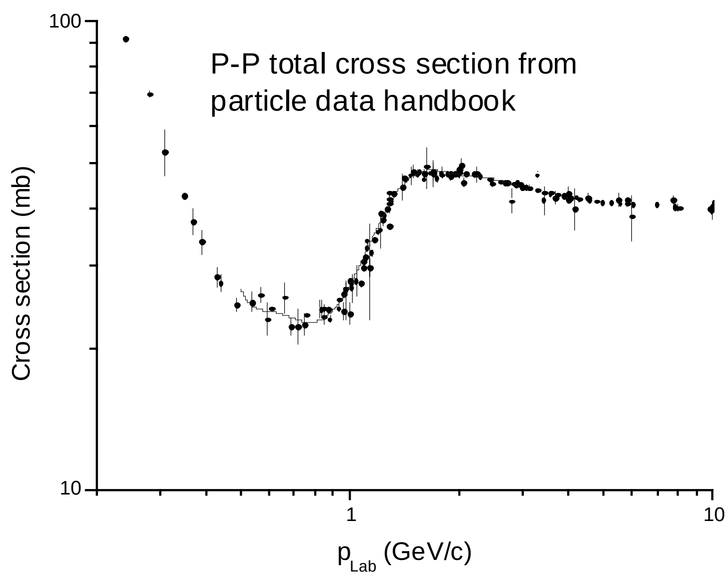

Figure 3. Proton-proton total cross sections. The rise in the 1–2 GeV/c region is mirrored in the data and calculations shown in Fig. 2. The solid curve is a polynomial fit used in the Glauber calculations. Note the horizontal axis is labeled by momentum, while that in Fig. 2 is labeled by kinetic energy.